Progress in the cryogenics work package

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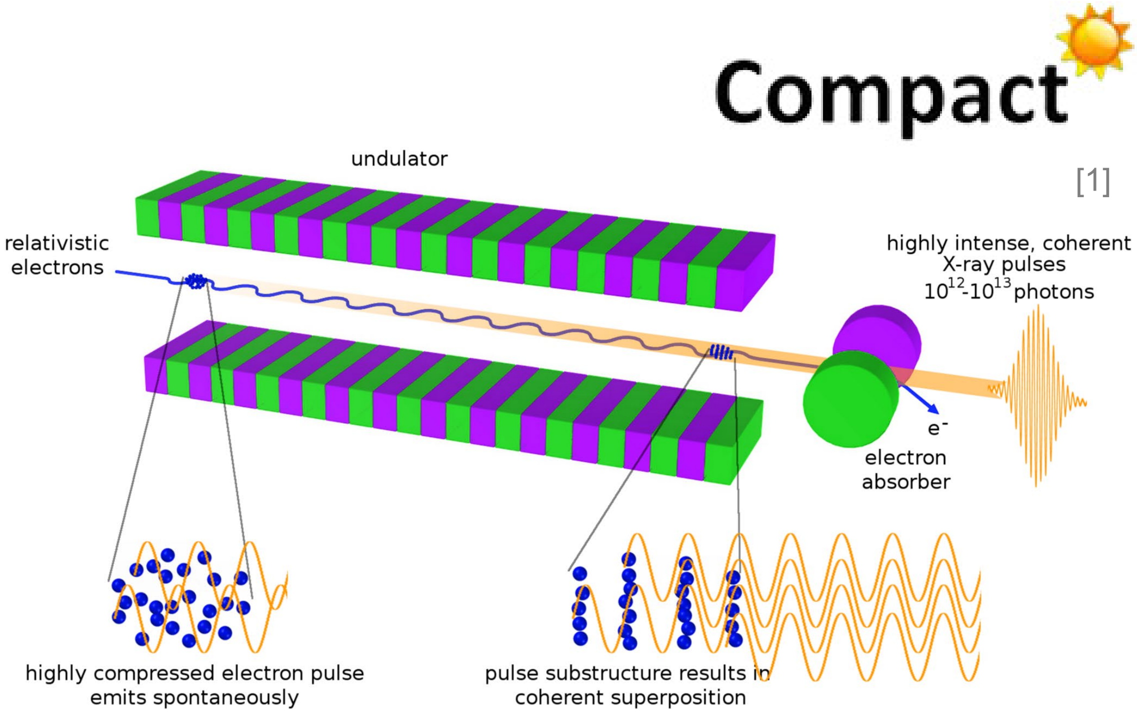
CompactLight design study

CompactLight design study

- Conceptual design study for next-generation hard X-ray free electron laser (FEL) facility
- Compared to existing FELs, the CompactLight facility will be more **compact** and will have a **lower energy demand** [1]

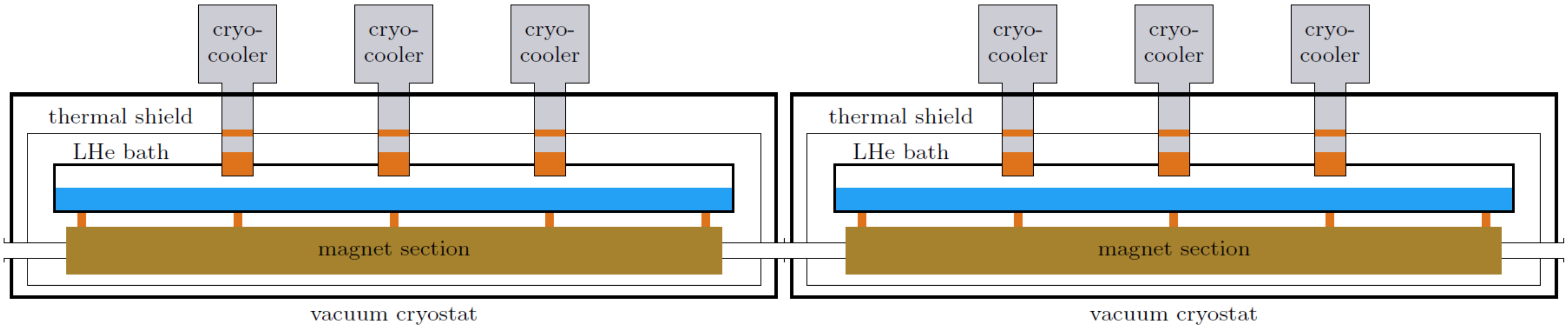
→ interesting for academic and industrial users

- The Self-Amplified Spontaneous Emission (SASE) line consists of 16 cryomodules containing several sc magnets [2]
  - Undulator
  - Phase shifter
  - Quadrupoles



Segmented design

- Individual cryostats for each magnet section in 4.2 K LHe-bath
- Flexibility in terms of mainenance
- Precise alignment
- Larger heat load due to cold-warm-transitions
- Vibrations and acoustic noise from cryocolers



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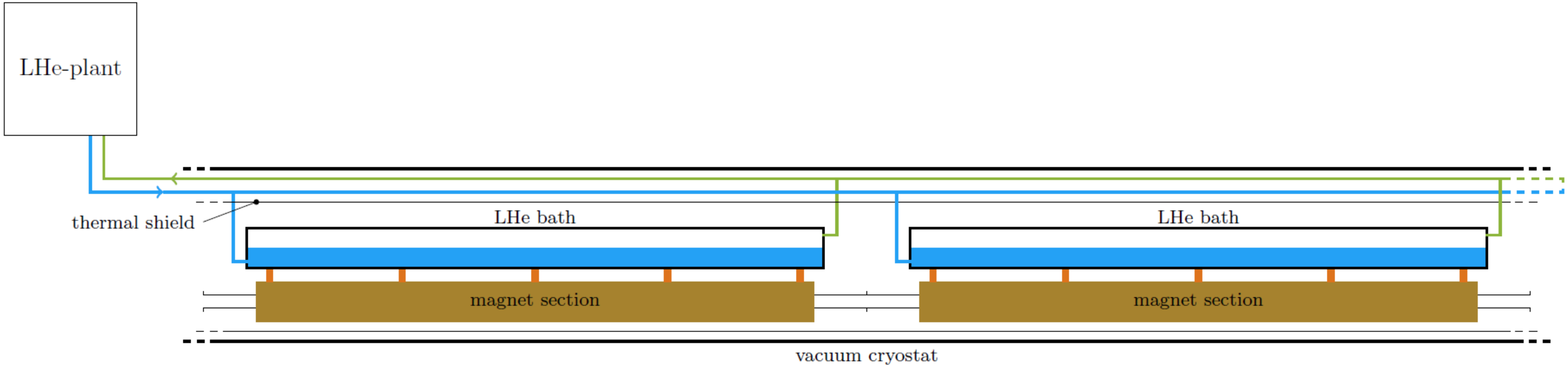
Minimal-segmented design

- Reduced cryostat complexity
- Maintenance-free cooling system inside the cryostat
- Smaller heat load as there are no cold-warm transitions



Heat load estimation

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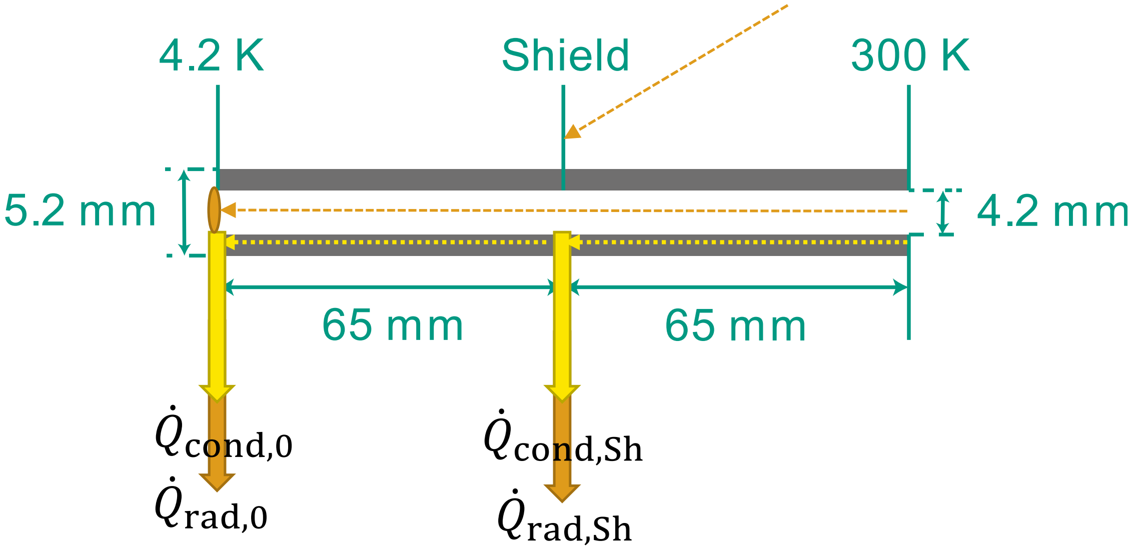
Assumptions – beam tube geometry

- Schematic view of assumed beam tube geometry



- Heat conducted along beam tube

$$\dot{Q}_{\mathrm{cond,12}} = \frac{A}{L}\int_{T_1}^{T_2} \lambda_{\mathrm{SST}}(T)\mathrm{d}T$$

- Radiation from ambient temperature is absorbed by black body

$$\dot{Q}_{\mathrm{rad,0}} = A_{\mathrm{BT}}\sigma(T_{\mathrm{a}}^4 - T_0^4)$$

- Radiation from cryostat to shield is given by

$$\dot{Q}_{\mathrm{rad,Sh}} = A_{\mathrm{Sh}}C_{\mathrm{Sh}}\sigma(T_{\mathrm{a}}^4 - T_{\mathrm{Sh}}^4)$$

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Assumptions – cryomodules & current leads

- Heat loads from magnets and cryomodules
  - Heat load 1 W/m according to Fuerst et al. [3]
  - 0.5 W per module due to instrumentation

→ Per module $\dot{Q}_{\mathrm{intern,0}} = 2.8\ \mathrm{W}$

- Number of magnets and supply currents:

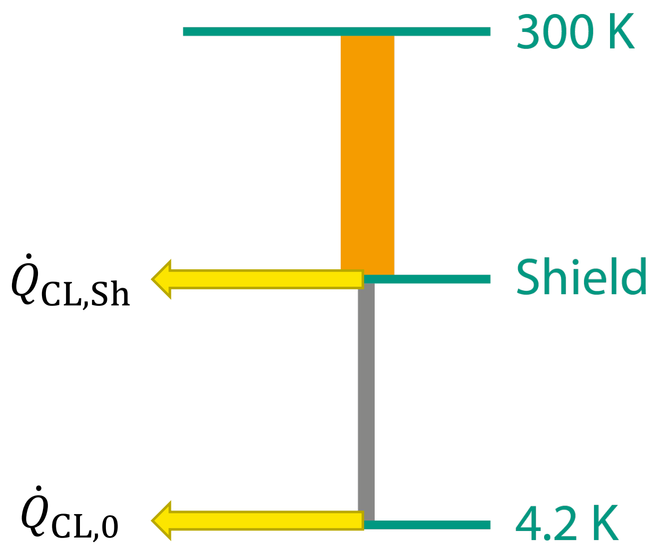
Magnet system	Number of magnets	Supply currents I / A
Undulators	1	500
Quadrupoles	2	100
Phase shifter	6	200

- Copper current leads from ambient to shield

  → Heat load of $\dot{Q}_{\mathrm{CL,Sh}} = 43\ \mathrm{W/kA}$ bei T_{sh}

- HTS-current leads from shield to magnets

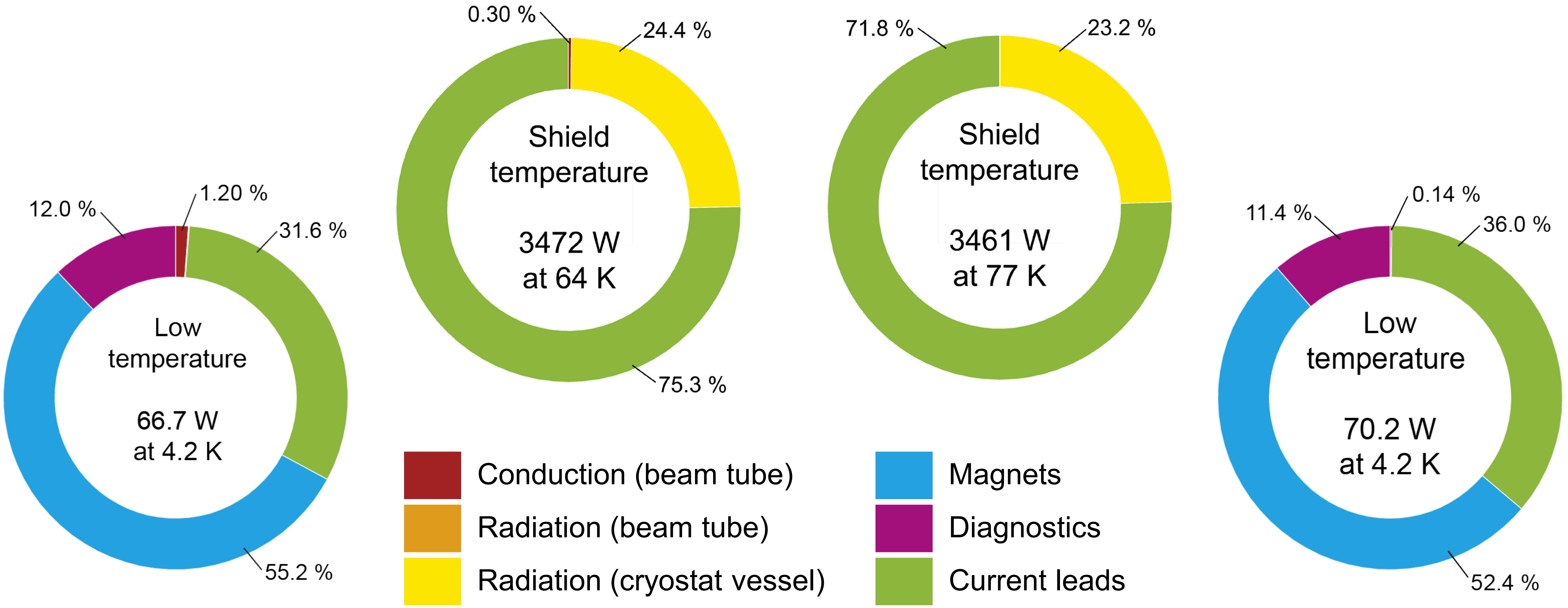
  → $\dot{Q}_{\mathrm{CL,0}}(I) = 65\ \mathrm{mW} - 235\ \mathrm{mW}$



Heat load estimation – Results

Segmented design (Cryocooler)

Minimal-segmented design (LHe-plant)



Refrigeration system

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Segmented Design

- At least 3 Cryocooler (2 W @ 4.2 K) per module needed

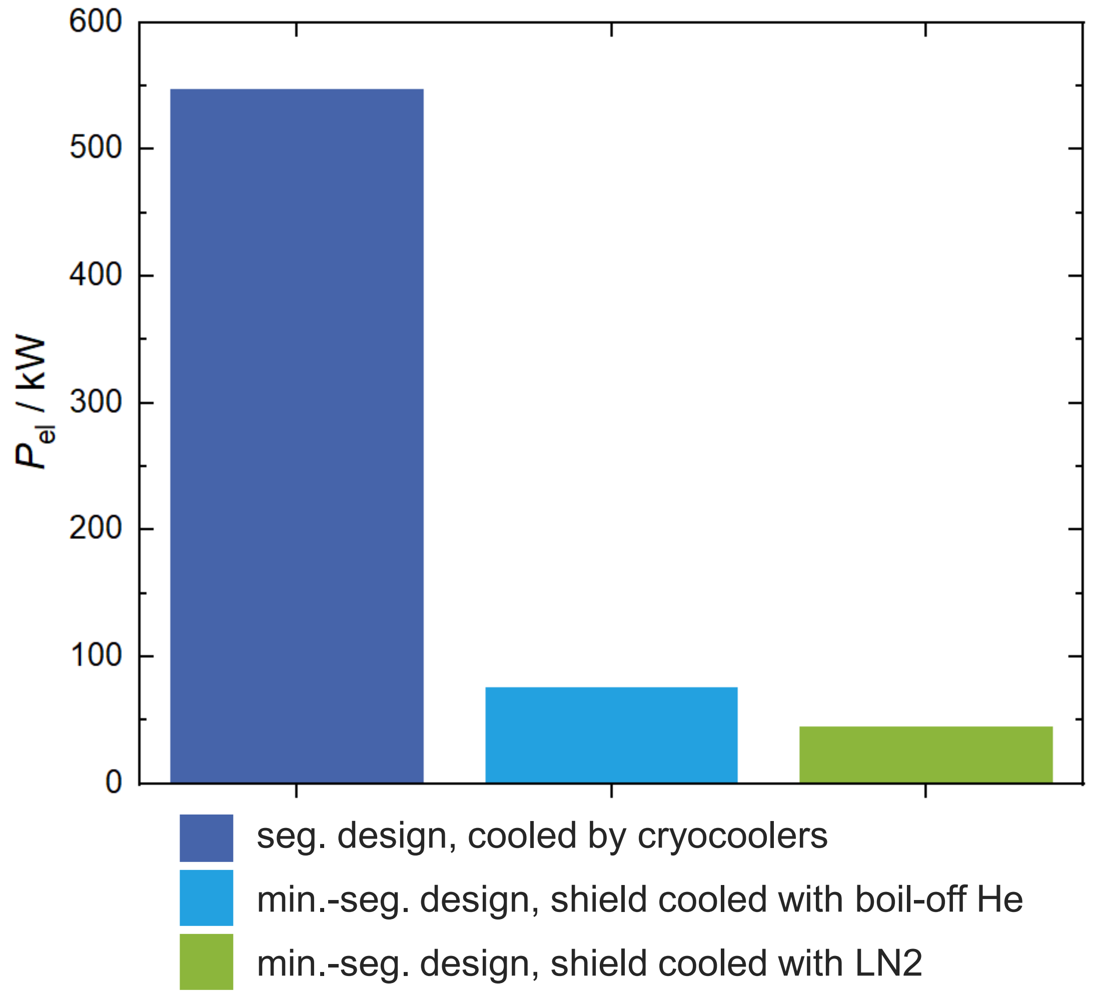
→ 48 Cryocooler per beam line

- Investment costs of about **2.4 M€**

Minimal-segmented Design

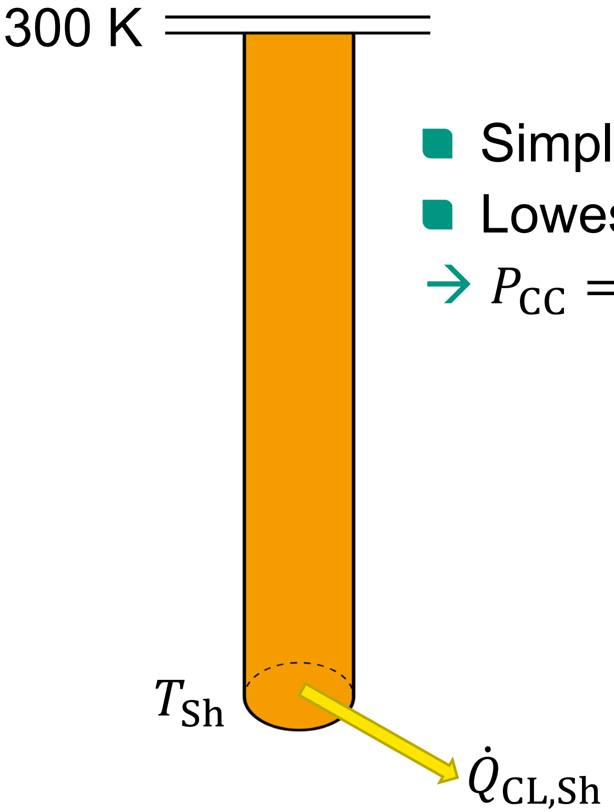
- Smallest LHe-plant of Linde (LR70) sufficient
- Cooling of shield with LN_2 or boil-off He
- Investment costs of about **2.1 M€**

Investment costs almost identical, power consumption crucial!



System comparison

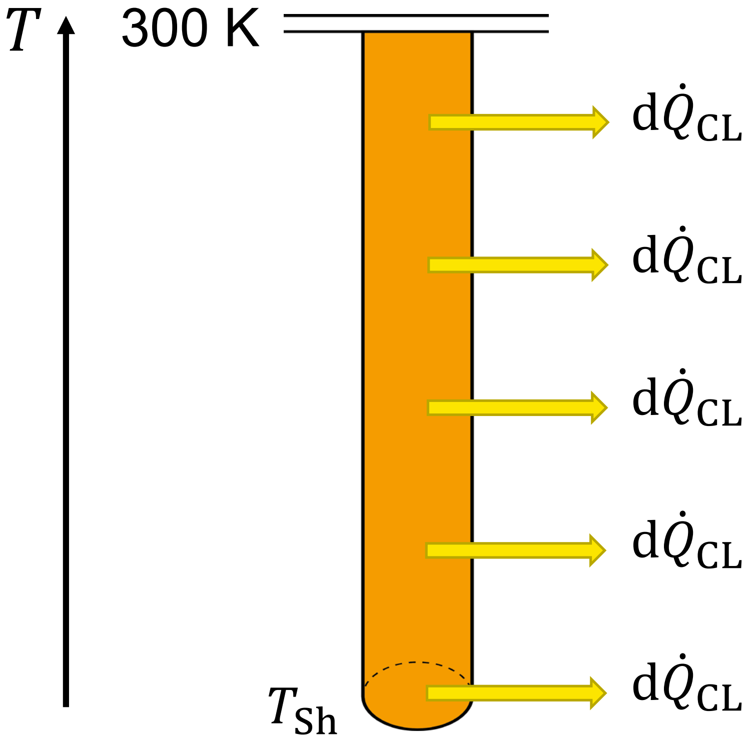
- Conduction cooled current leads



- Simplest design
- Lowest efficiency

→ $P_{\mathrm{CC}} = f(T)$

- CMRC-cooled current leads



- Heat absorption directly at the source

→ High efficiency

$$P_{\mathrm{CMRC}} = \frac{1}{3} \cdot P_{\mathrm{CC}}$$ [4]

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Development of CMRC-cooled current leads

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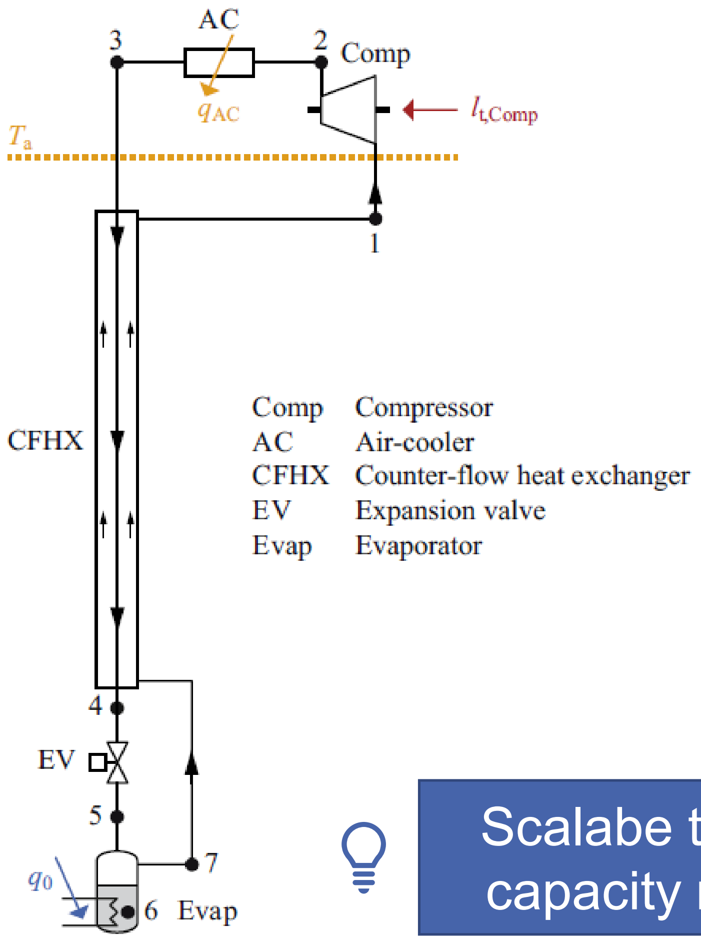
Mixed-refrigerant cycles (MRCs)

- The key player in every cooling system is the working fluid, especially
  - its state and transport properties (EoS)
  - its changes of state during the thermodynamic process/cycle

select pure fluid fitting your demands the best	„design“ desired fluid properties and behaviour
↓	↓
„design“ process to optimize efficiency	use „simple“ process with high efficiency



Scalabe to any capacity range

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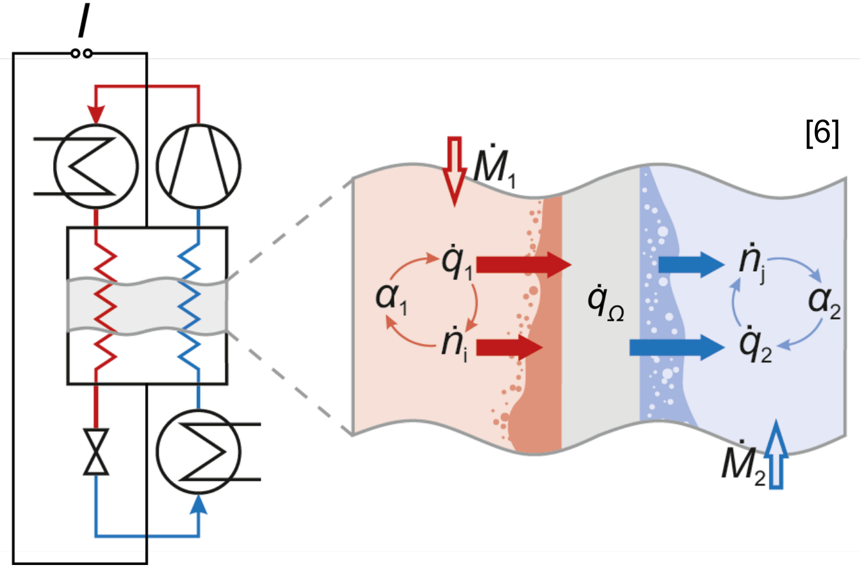
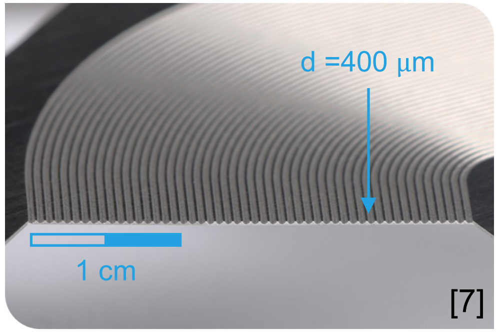
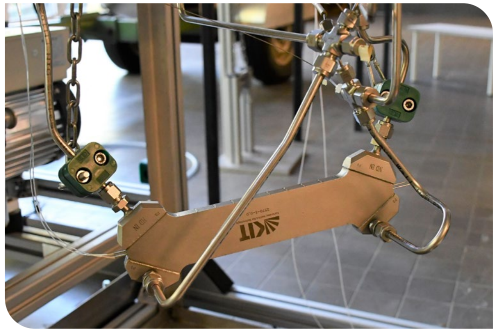
CMRC-cooled micro-structured current leads

- Numerical model for heat exchanger calculation [5]
  - Iterative solution of energy and momentum conservation
  - Description of heat and mass transport in two-phase flow
  - Thermal-electric integration of ohmic losses
  - Longitudinal and parasitic heat flow



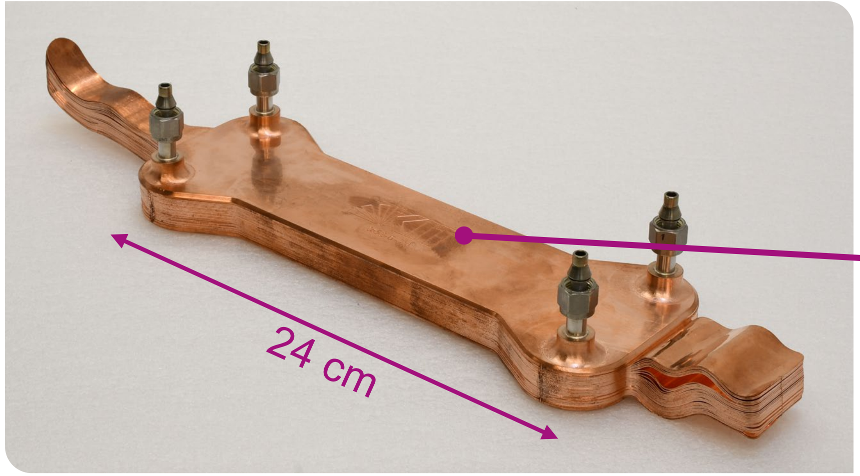
- Development of new heat exchanger technology
  - High efficieny by small gradients
    → large heat transfer area
  - Development of minichannel heat exchangers

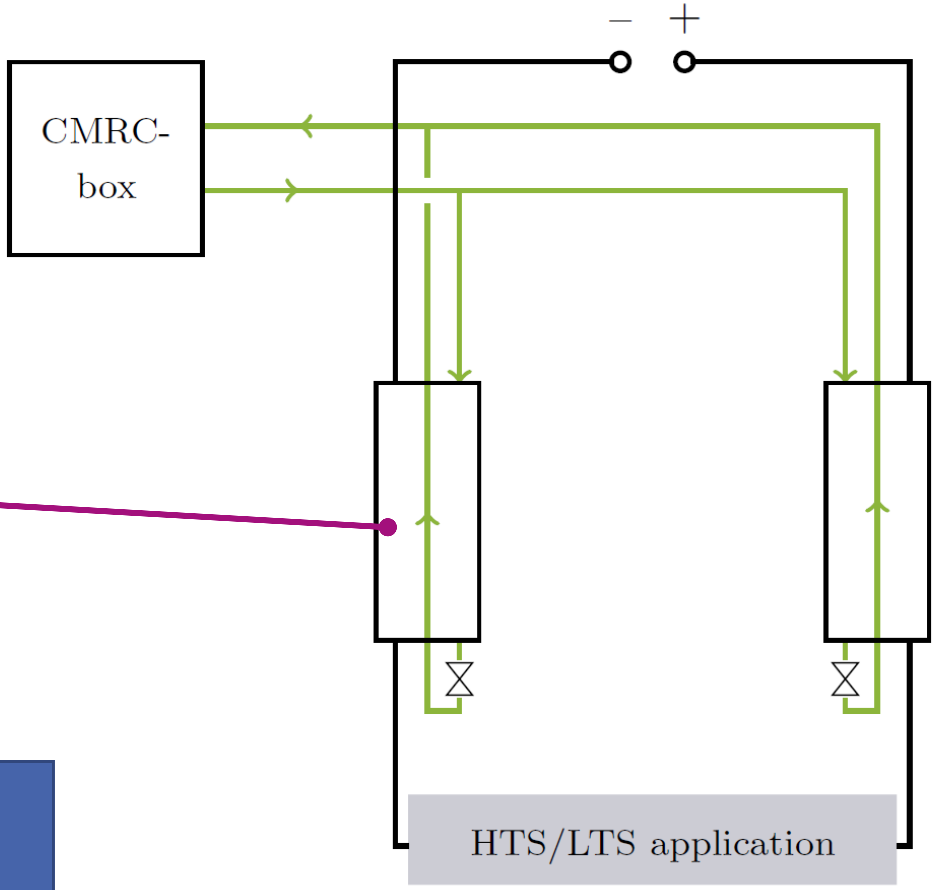




Micro-structured Current Leads

- Easy scalability due adjustable construction by sheets
  - Ultra compact – prototype only 24 cm long
  - Ultra efficient – heat absorption at the source





Scalable technology allows development of **compact high-efficient** current leads for **any** current range!

Compact Accelerator Systems Teststand (COMPASS)

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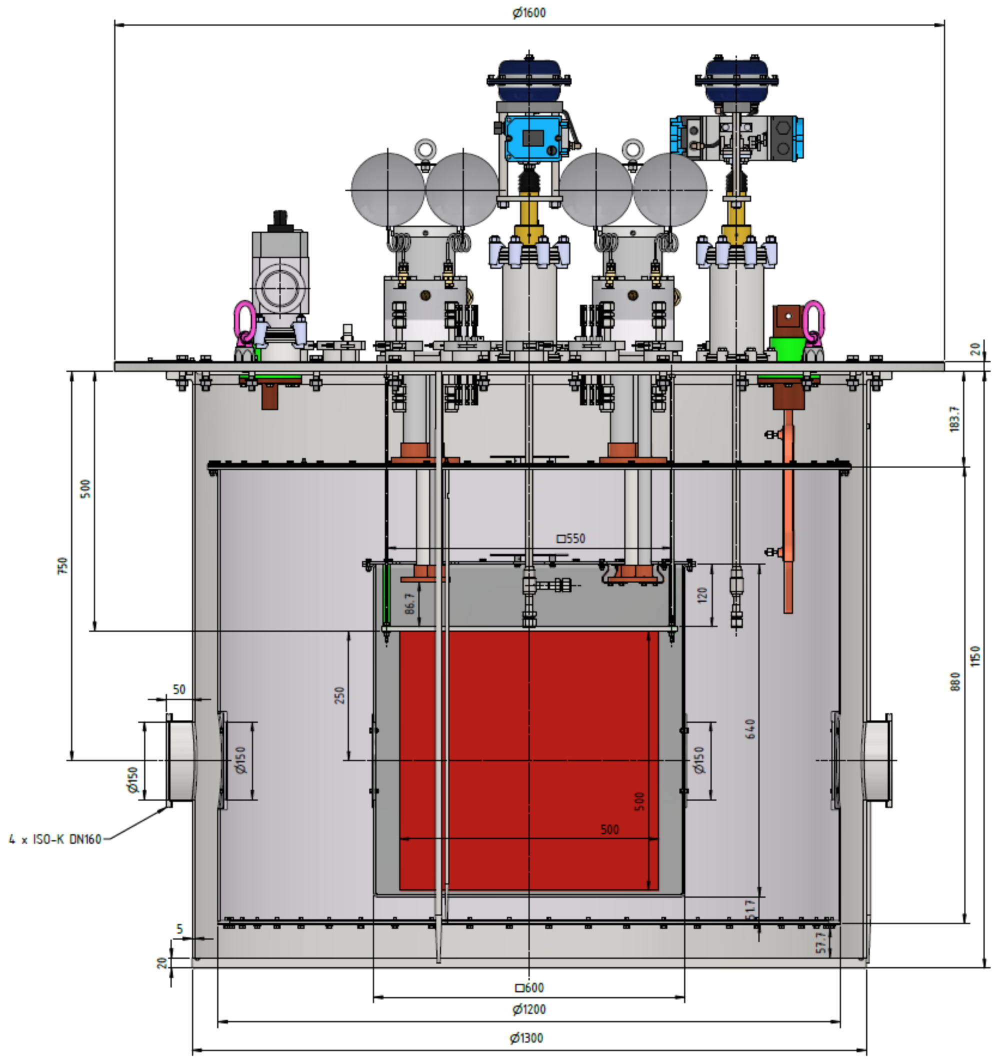
Copact Accelerator Teststand (COMPASS) Cryostat Design

- Test stand for experimental investigation of CMRC-cooled current leads
  - CMRC-cascade system to reach temperatures down to 55 K
  - Experiments with supply currents up to 10 kA possible

- Field measurements in LTS-magnets possible
  - Free space for cold mass 50x50x50 cm³
  - Current supply via two seperate circuits
  - CMRC-cooled and classical conduction cooled current leads



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Summary & Outlook

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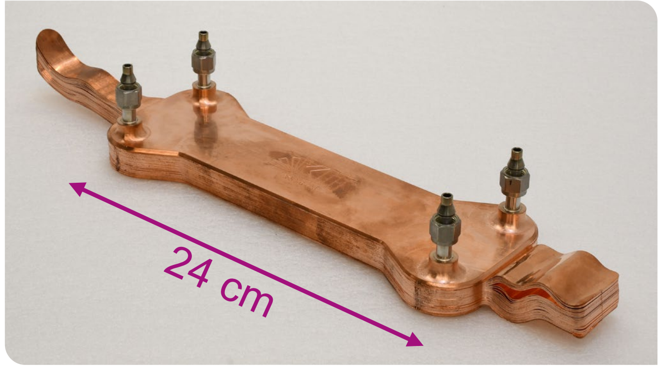
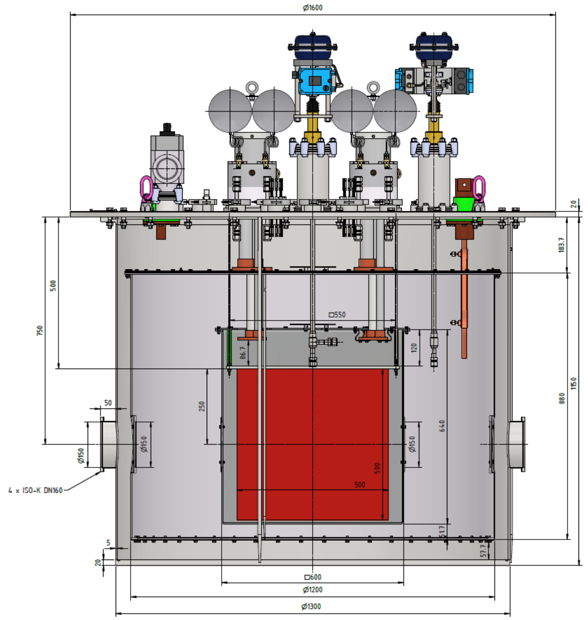
Summary & Outlook

- CompactLight design study shows **75 %** of cryogenic heat load arises from current leads
- Low energy efficiency for cryocooler-(conduction)-cooled current leads
- Current leads cooled by mixed-refrigerant cycles promise **reduction of power demand by 66 %**
- Advantages of micro-structured current lead technology
  - **Ultra compact** – first prototype only 24 cm long
  - **Ultra efficent** – heat absorption at the source
  - **Simple scalability** – for any current range
- COMPASS Test Stand for experimental investigation of current leads and magnet systems under development





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Literature

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[1] https://www.compactlight.eu/Main/HomePage, last checked 04.11.2021.

[2] F. Nguyen et al., CompactLight Deliverable D5.2, „Design Studies for the Undulator“, 2021.

[3] J.D. Fuerst. Et al., „Review of New Developments in Superconducting Undulator Technology at the APS“, 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources“, FLS2018, Shanghai, China, 2018.

[4] E. Shabagin, „Development of a CMRC cooled 10 kA current lead for HTS applications, PhD thesis, Karlsruhe Institute of Technology, Karlsruhe, to be published.

[5] D. Gomse, „Development of heat exchanger technology for cryogenic mixed-refrigerant cycles,“ PhD thesis, Karlsruhe Institute of Technology, Karlsruhe, 2019.

[6] D. Gomse, S. Grohmann, „Heat transfer and pressure drop in the main heat exchanger of a cryogenic mixed refrigerant cycle”, en, 2018. ICEC27-ICMC 2018, Oxford, England, September 3-7 2018.

[7] D. Gomse, T. Kochenburger, J. Brandner, S. Grohmann, „Entwicklung eines Wärmeübertragers für kryogene Gemischkältekreisläufe“, de, 2016. DKV Tagung Kassel, AA.I.19, 18.11.2016.